THE UNIVERSITY OF ALABAMA

Coupled Nonlinear Aeroelasticity and Flight Dynamics of Highly Flexible Aircraft

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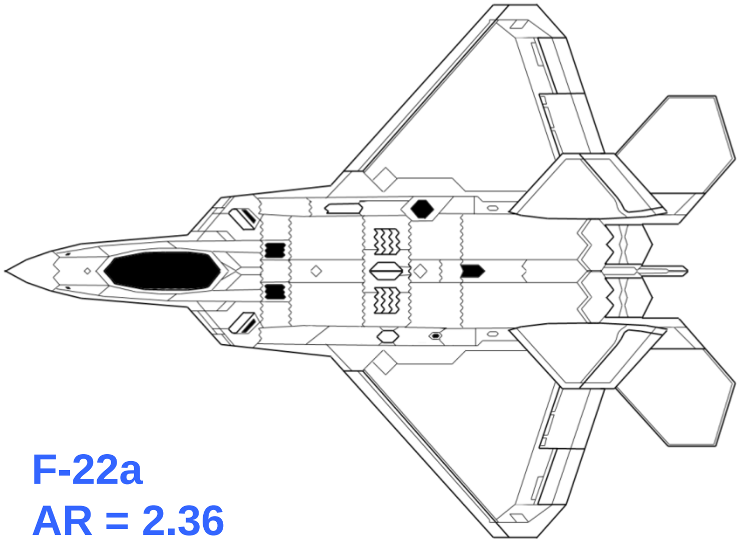
Overview

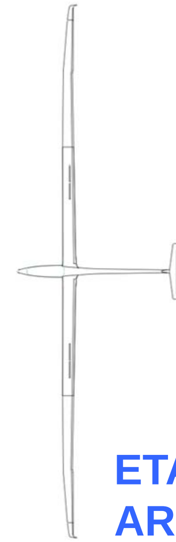
- Introduction
  - Background
  - Motivation
- Theoretical formulation
  - Geometrically nonlinear beam
  - Unsteady aerodynamics
  - Flight dynamic modeling
- Numerical studies
- Concluding remarks
- Ongoing and future developments

Aerodynamic Efficiency and Wing Aspect-Ratio



F-22a
AR = 2.36

B787-8
AR = 11.08



ETA (Germany)
AR = 51.33

Large wing aspect-ratio to achieve high aerodynamic efficiency

$$R \text{ or } E \propto \left(\frac{L}{D}\right) \ln\left(\frac{W_0}{W_1}\right)$$

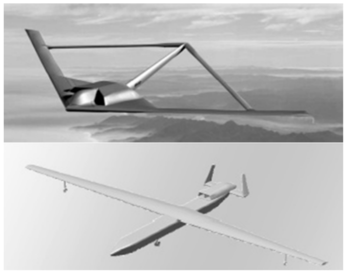
High aerodynamic efficiency

What about Structural Design?

- U.S. Air Force Sensorcraft studies
  - High-altitude, long-endurance
  - Unmanned vehicles
  - Sensor platform
  - Very high fuel fractions (up to 60%)

$$R \text{ or } E \propto \left(\frac{L}{D}\right)\ln\left(\frac{W_0}{W_1}\right)$$

- Very light structures
  - Not necessarily carry fuel, but…



Low structural weight fraction

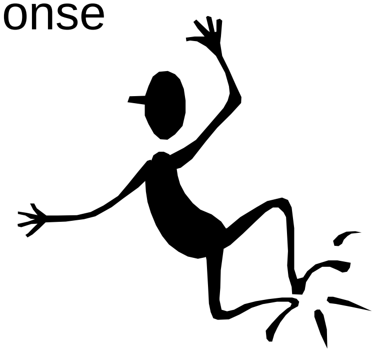
+

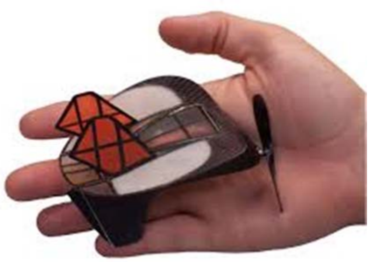
High-aspect-ratio wings

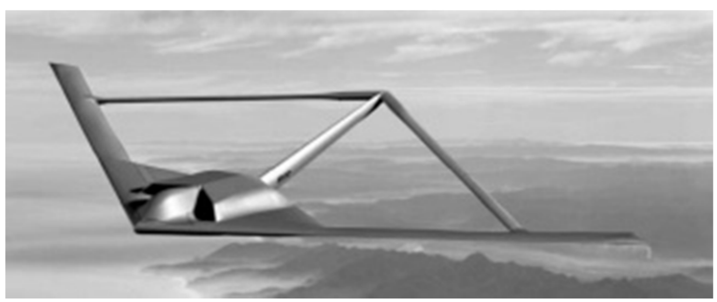
→ ***Highly flexible aircraft***

What’s Challenging?

- Large wing deformation
  - Linear solution might not be sufficient
  - Nonlinear solution needed
- Coupling between wing oscillation and rigid-body motion
  - Coupled transient response
  - Body freedom flutter
- Other effects
  - Low Reynolds flights
  - Local transonic effects





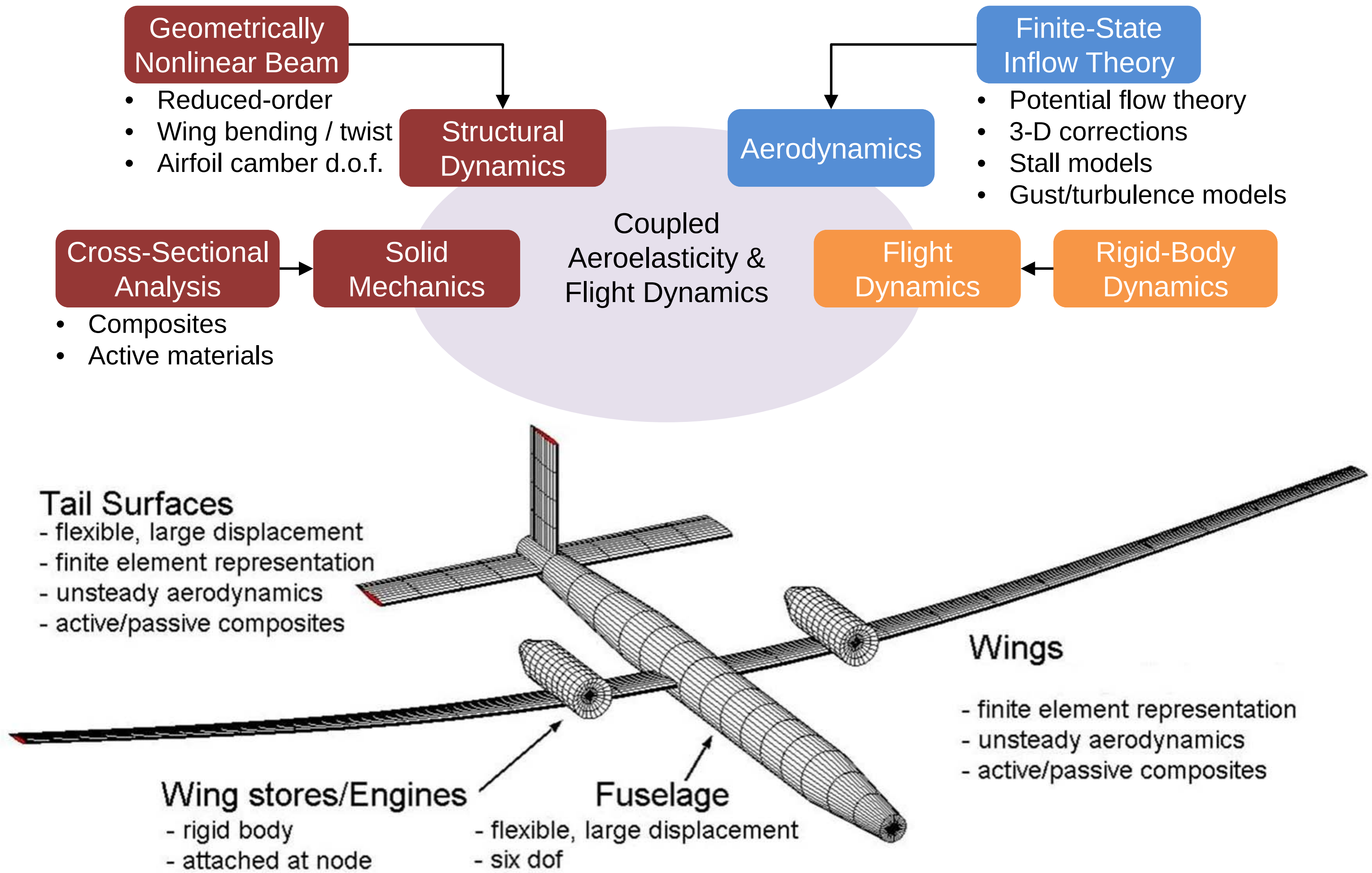


Need an integral solution for nonlinear aeroelasticity + flight dynamics

Objectives

- Create a low-order aeroelastic and flight dynamic framework
  - Effectively represent dynamic behavior of highly flexible vehicle
  - Efficient solution
  - Facilitate active aeroelastic tailoring and control studies
- Explore structural, aerodynamic, and control techniques to enhance flight efficiency and performance
  - Reduce drag
  - Reduce power consumption
  - Suppress instability
  - Reject air disturbance

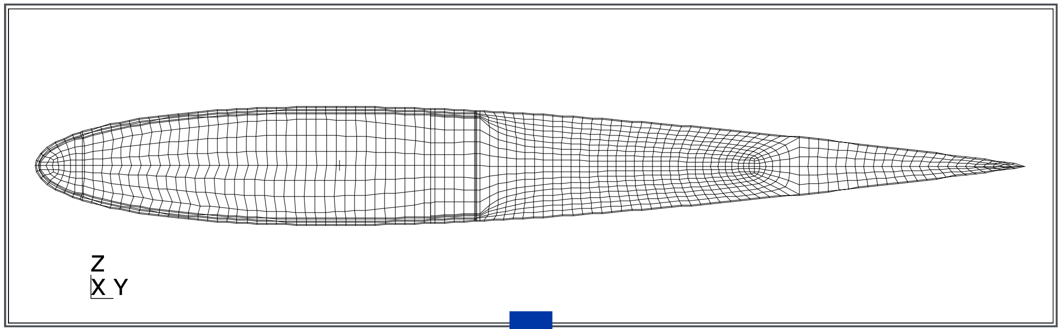
Coupled Nonlinear Aeroelasticity and Flight Dynamics



A simplified aeroelastic/flight dynamics simulation system

Reduced-Order Structural Modeling

- From 3D elastic problem to <u>2D beam cross-sectional analysis</u> and <u>1D beam model</u>
- Dimensional reduction using the Variational-Asymptotic Method:
  - Active thin-walled solution (mid-line discretization)
  - VABS (finite-element discretization)
  - User defined stiffness constants



Cross-Section Stiffness and Inertial Properties

$$\begin{bmatrix} F_x \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{21} & K_{22} & K_{23} & K_{24} \\ K_{31} & K_{32} & K_{33} & K_{34} \\ K_{41} & K_{42} & K_{43} & K_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$

Basic Coordinate Systems

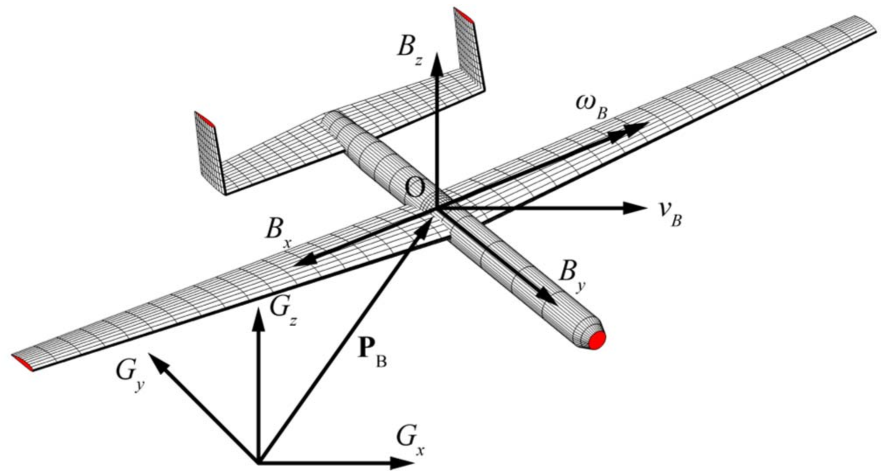
- Global frame (G)
- Body frame (B) – origin not necessary to be C.G. of vehicle
- Body frame motion variables

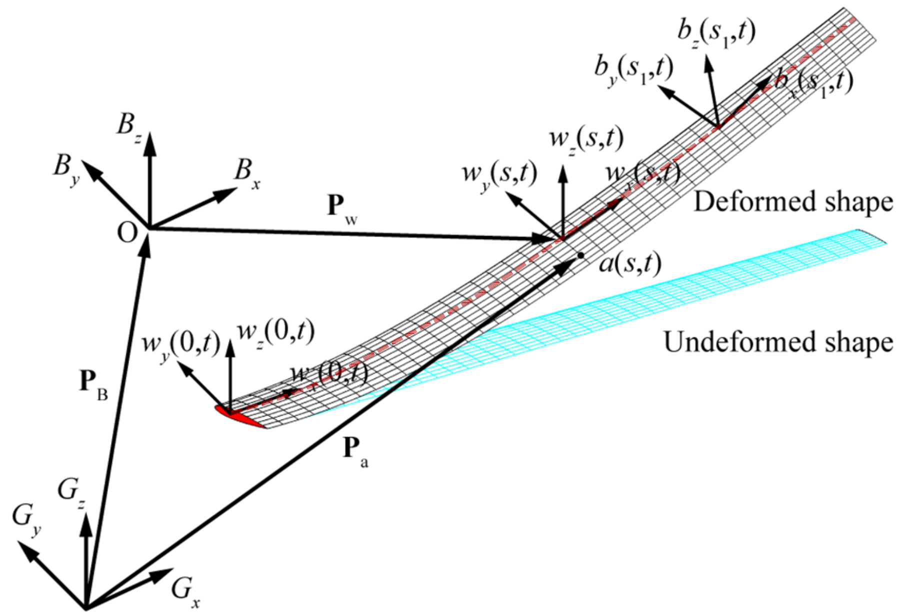
$$b = \begin{Bmatrix} p_B \\ \theta_B \end{Bmatrix}$$

$$\dot{b} = \beta = \begin{Bmatrix} \dot{p}_B \\ \dot{\theta}_B \end{Bmatrix} = \begin{Bmatrix} v_B \\ \omega_B \end{Bmatrix}$$

$$\ddot{b} = \dot{\beta} = \begin{Bmatrix} \ddot{p}_B \\ \ddot{\theta}_B \end{Bmatrix} = \begin{Bmatrix} \dot{v}_B \\ \dot{\omega}_B \end{Bmatrix}$$

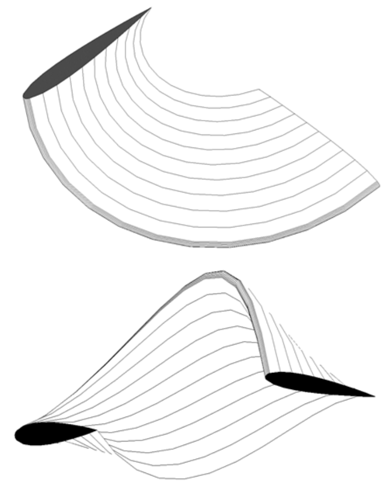
- Local beam frame (w)
- Auxiliary local frame (b)



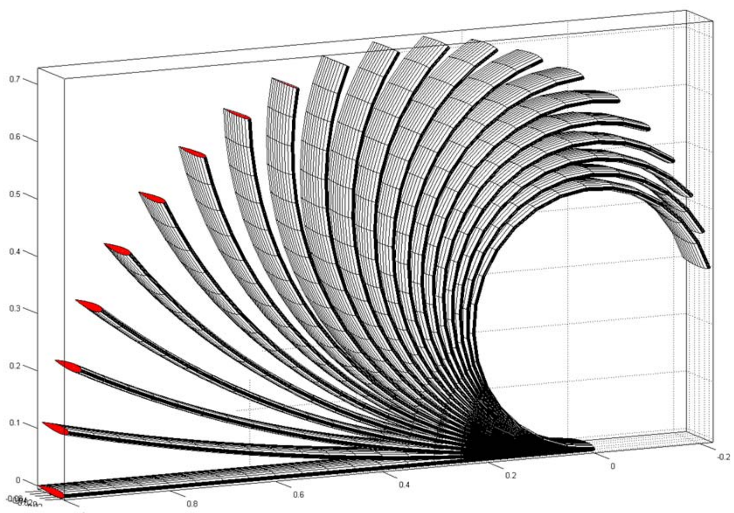


Strained-Based Geometrically Nonlinear Beam Formulation

- Geometrically nonlinear beam formulation[1]
- Four local strain degrees-of-freedom (ε): extension, twist, flatwise bending, and chordwise bending
- Constant-strain elements
- Capture large complex deformations with fewer elements – computationally efficient
- Isotropic and anisotropic constitutive relations



Sample element deformations with constant strain



Strains (ε) and body velocities (β) are independent variables

[1] Su, W., and Cesnik, C.E.S., “Strain-Based Geometrically Nonlinear Beam Formulation for Modeling Very Flexible Aircraft,” *International Journal of Solids and Structures*, Vol. 48, No. 16-17, 2011, pp. 2349-2360. (doi: 10.1016/j.ijsolstr.2011.04.012)

Formulation Based on Principle of Virtual Work

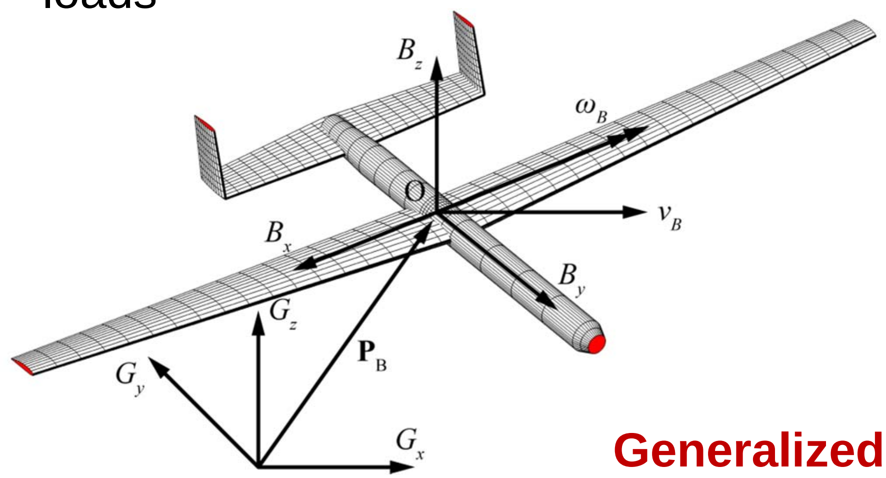
Internal VW

External VW

$$\sum_i \delta W_i = 0$$

Equations of Motion

- Inertia force, internal strain, and strain rate
- Gravity loads, distributed loads, and point loads



Generalized Force

$$\begin{bmatrix} M_{FF}(\varepsilon) & M_{FB}(\varepsilon) \\ M_{BF}(\varepsilon) & M_{BB}(\varepsilon) \end{bmatrix} \begin{Bmatrix} \ddot{\varepsilon} \\ \dot{\beta} \end{Bmatrix} + \begin{bmatrix} C_{FF}(\varepsilon,\dot{\varepsilon},\beta) & C_{FB}(\varepsilon,\dot{\varepsilon},\beta) \\ C_{BF}(\varepsilon,\dot{\varepsilon},\beta) & C_{BB}(\varepsilon,\dot{\varepsilon},\beta) \end{bmatrix} \begin{Bmatrix} \dot{\varepsilon} \\ \beta \end{Bmatrix} + \begin{bmatrix} K_{FF} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \varepsilon \\ b \end{Bmatrix} = \begin{Bmatrix} R_F \\ R_B \end{Bmatrix}$$

Generalized Mass **Generalized Damping** **Generalized Stiffness**

$$\begin{Bmatrix} R_F \\ R_B \end{Bmatrix} = \begin{Bmatrix} K_{FF}\varepsilon^0 \\ 0 \end{Bmatrix} - \begin{bmatrix} J_{h\varepsilon}^T \\ J_{hb}^T \end{bmatrix} Ng + \begin{bmatrix} J_{p\varepsilon}^T \\ J_{pb}^T \end{bmatrix} B^F F^{dist} + \begin{bmatrix} J_{\theta\varepsilon}^T \\ J_{\theta b}^T \end{bmatrix} B^M M^{dist} + \begin{bmatrix} J_{p\varepsilon}^T \\ J_{pb}^T \end{bmatrix} F^{pt} + \begin{bmatrix} J_{\theta\varepsilon}^T \\ J_{\theta b}^T \end{bmatrix} M^{pt}$$

Recovery of Nodal Displacement

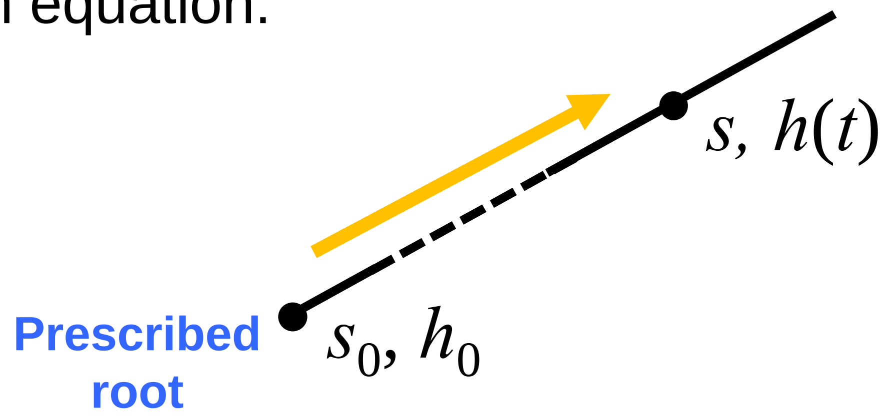
- Solution of displacement-strain equation:

$$\frac{\partial h(s)}{\partial s} = A(s)h(s)$$

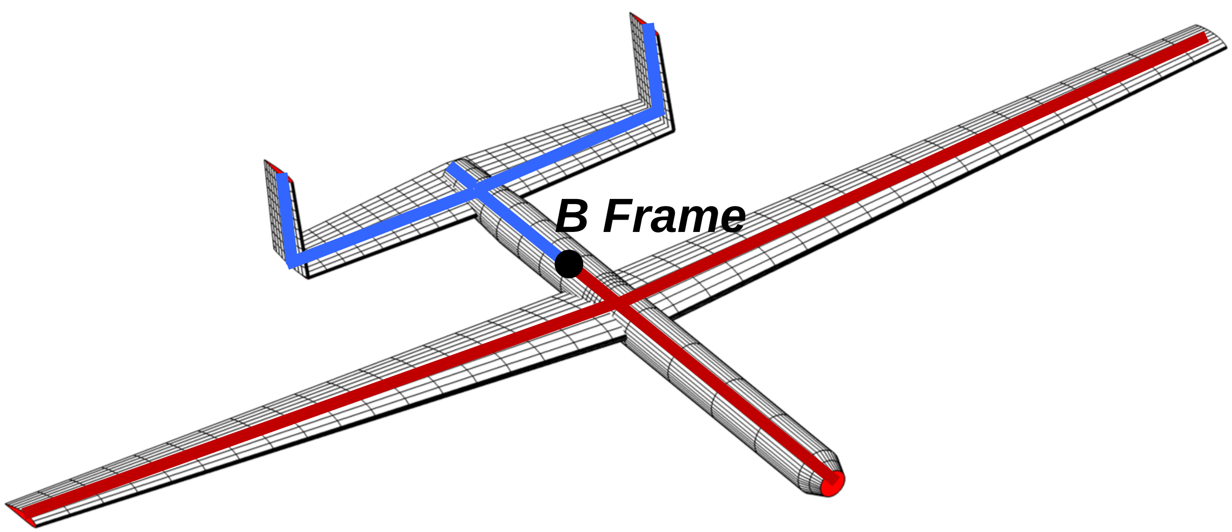
$$\Downarrow$$

$$h(s) = e^{A(s)\cdot(s-s_0)}h_0 = e^{G(s)}h_0$$

B.C.



- Marching kinematics in complete aircraft



Unsteady Aerodynamics

- 2-D Theodorsen-like unsteady aerodynamics (Peters et al., 94, 95)

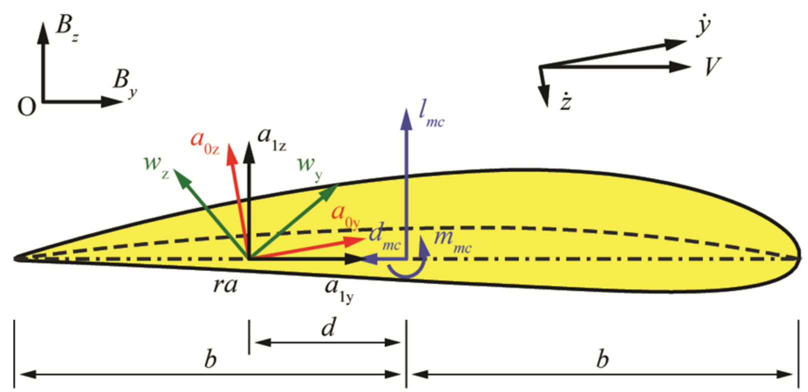
Inflow velocity

$$l_{mc} = \pi\rho_\infty b^2\left(-\ddot{z} + \dot{y}\dot{\alpha} - d\ddot{\alpha}\right) + 2\pi\rho_\infty b\dot{y}^2\left[-\frac{\dot{z}}{\dot{y}} + \left(\frac{1}{2}b - d\right)\frac{\dot{\alpha}}{\dot{y}} - \frac{\lambda_0}{\dot{y}}\right] + 2\pi\rho_\infty b c_1 \dot{y}^2\delta$$

$$m_{mc} = \pi\rho_\infty b^2\left(-\frac{1}{8}b^2\ddot{\alpha} - \dot{y}\dot{z} - d\dot{y}\dot{\alpha} - \dot{y}\lambda_0\right) + 2\pi\rho_\infty b^2 c_4 \dot{y}^2\delta$$

- Glauert expansion of inflow velocity as function of inflow states, λ_n

$$\lambda_0 = \frac{1}{2}\sum_{n=1}^{N} b_n\lambda_n$$

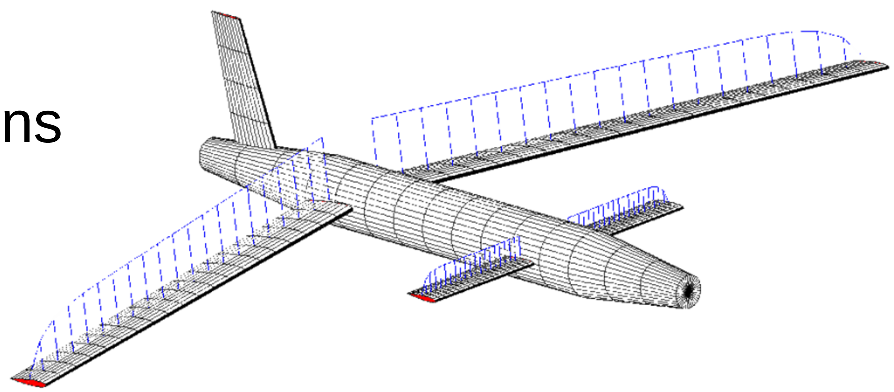


- Finite state differential equation is transformed to independent variables ε and β

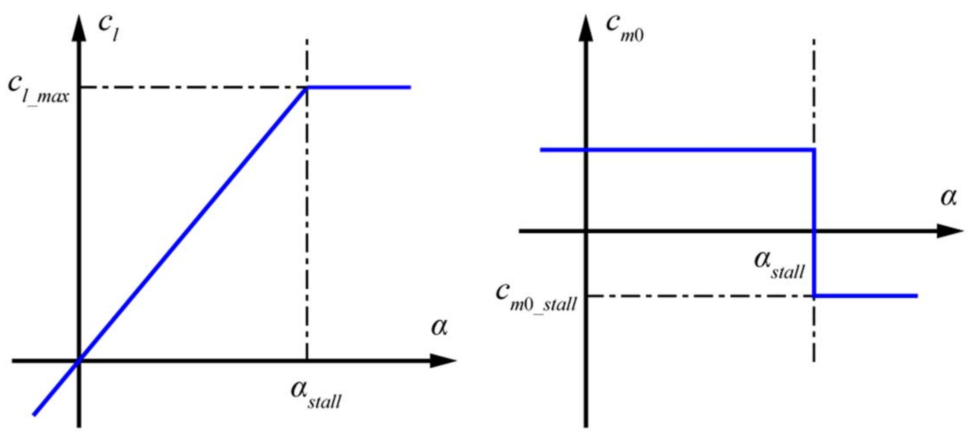
$$\dot{\lambda} = E_1\lambda + E_2\ddot{z} + E_3\ddot{\alpha} + E_4\dot{\alpha} \quad \Rightarrow \quad \left\{\dot{\lambda}\right\} = F_1\begin{Bmatrix}\ddot{\varepsilon}\\ \dot{\beta}\end{Bmatrix} + F_2\begin{Bmatrix}\dot{\varepsilon}\\ \beta\end{Bmatrix} + F_3\left\{\lambda\right\}$$

Finite-State Inflow Theory: Modifications

- Aerodynamic coefficient modifications based on XFoil (Re effects) or CFD calculations
- Compressibility accounted for by Prandtl-Glauert correction
- Spanwise aerodynamic corrections (3-D effects)



- Simplified stall model

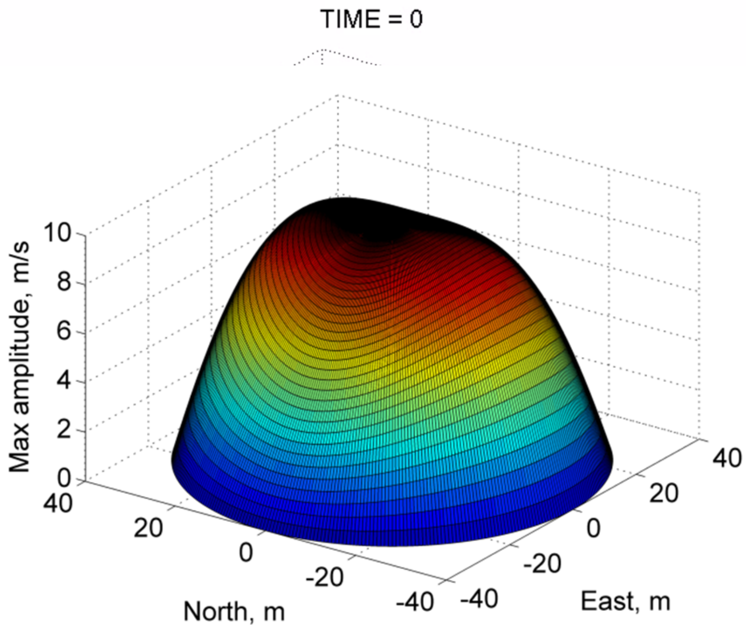


(a) Lift coefficient (b) Moment coefficient

Additional aerodynamic development in progress

Discrete Non-uniform Gust Model

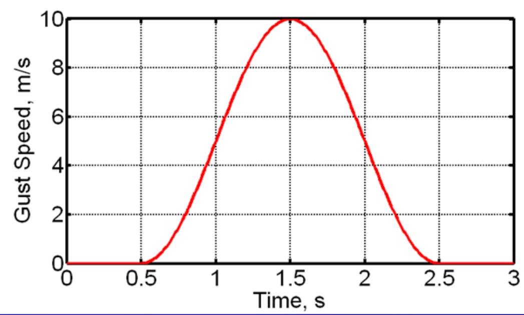
- Fixed region in space
- Amplitude distribution
  - Peak at center and zero at boundary
  - Possibly different distribution in East and North directions
  - Smooth transition



$$A(r,\eta,t)=\frac{1}{2}A_c\left[1-\cos\left(2\pi\frac{t}{t_g}\right)\right]\sqrt{\left(A_E\cos\eta\right)^2+\left(A_N\sin\eta\right)^2}$$

$$A_E(r)=\sin\left(\frac{\pi}{2}\left[1-\left(\frac{r}{r_0}\right)^{n_E}\right]\right)\quad,\quad A_N(r)=\sin\left(\frac{\pi}{2}\left[1-\left(\frac{r}{r_0}\right)^{n_N}\right]\right)\quad,\quad 0<r\le r_0$$

- Time variation: 1-cosine with different temporal durations



Dryden Gust Model

- Gust PSD function

$$\Phi_w(\omega_m) = \frac{\sigma_w^2 L_w \left[1 + 3\left(\frac{L_w \omega_m}{U_0}\right)^2\right]}{\pi U_0 \left[1 + \left(\frac{L_w \omega_m}{U_0}\right)^2\right]^2}$$

MIL-F-8785C

$$\Phi_w(\omega_m) = \frac{2\sigma_w^2 L_w \left[1 + 12\left(\frac{L_w \omega_m}{U_0}\right)^2\right]}{\pi U_0 \left[1 + 4\left(\frac{L_w \omega_m}{U_0}\right)^2\right]^2}$$

MIL-HDBK-1797

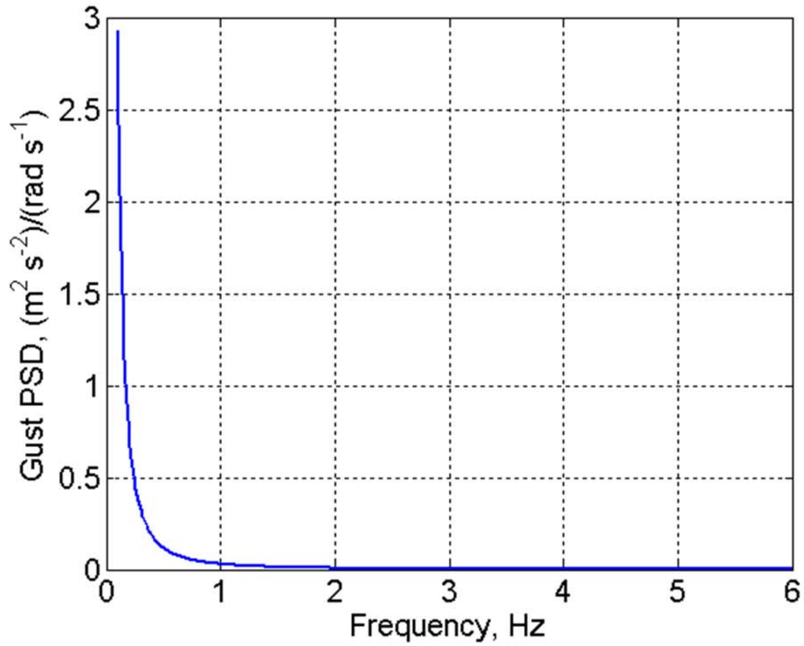
- ω_m: Frequency component (rad/s)
- U_0: Free stream velocity (m/s)
- L_w: Scale of turbulence (m), determined by altitude (m)
- Superposition of all frequency components with random phase

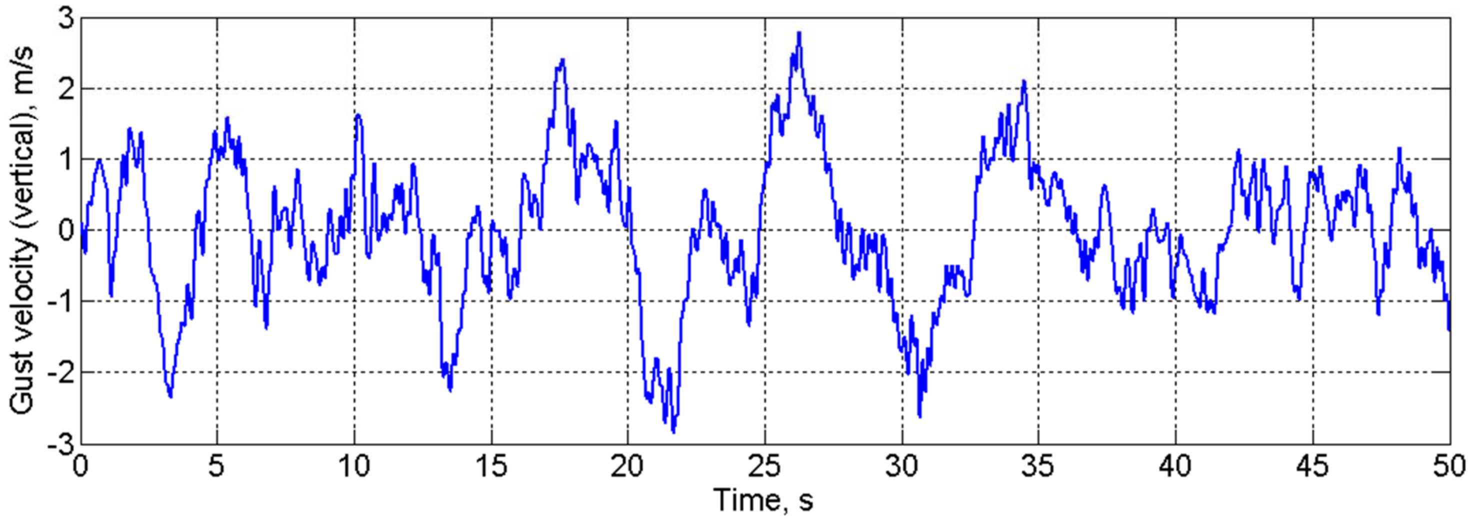
$$w(t) = \sum_{m=1}^{\infty} \sqrt{\Phi_w(\omega_m)\Delta\omega}\cos(\omega_m t + \psi_m)$$

PSD and Time History of Gust Velocity

- Frequency band [0.1~6] Hz
- σ_w adjusted to obtain enough wing deformation
- Uniform spanwise distribution

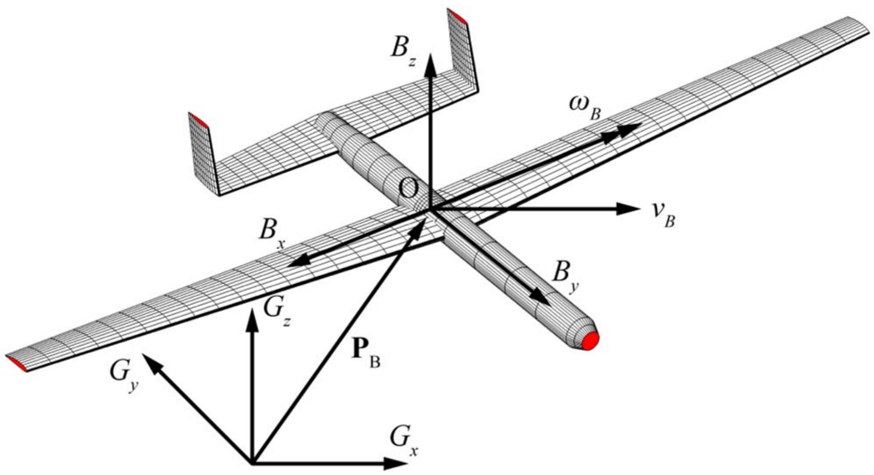
Power concentrated at the low frequency range

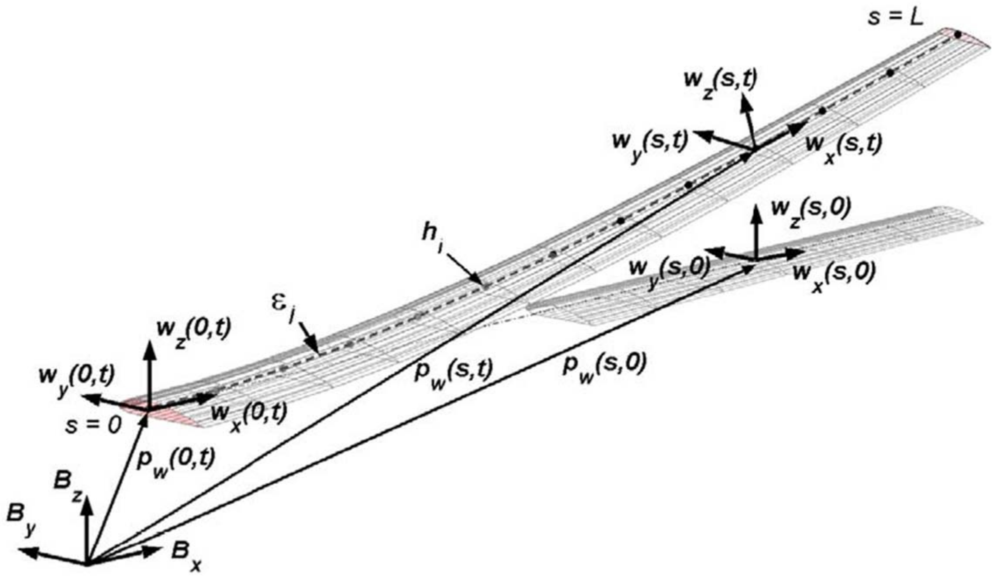




Flight Dynamics Modeling

The trajectory and orientation of a fixed body reference frame, *B*, at point *O*, which in general is *not* the aircraft's center of mass





Full Air Vehicle Model for Flight Simulations

- Elastic equations of motion

Strains (4 by m structural d.o.f.)

$$M(\varepsilon)\begin{Bmatrix}\ddot{\varepsilon}\\ \dot{\beta}\end{Bmatrix}+C(\varepsilon,\dot{\varepsilon},\beta)\begin{Bmatrix}\dot{\varepsilon}\\ \beta\end{Bmatrix}+K\begin{Bmatrix}\varepsilon\\ b\end{Bmatrix}=R(\varepsilon,\dot{\varepsilon},\ddot{\varepsilon},\zeta,\beta,\dot{\beta},\lambda,u)$$

Control inputs

Body velocities (6 flight dynamic d.o.f.)

- Finite-state 2-D unsteady aerodynamics

Inflow states (N by m aerodynamic d.o.f.)

$$\dot{\lambda}=F_1\begin{Bmatrix}\ddot{\varepsilon}\\ \dot{\beta}\end{Bmatrix}+F_2\begin{Bmatrix}\dot{\varepsilon}\\ \beta\end{Bmatrix}+F_3\lambda$$

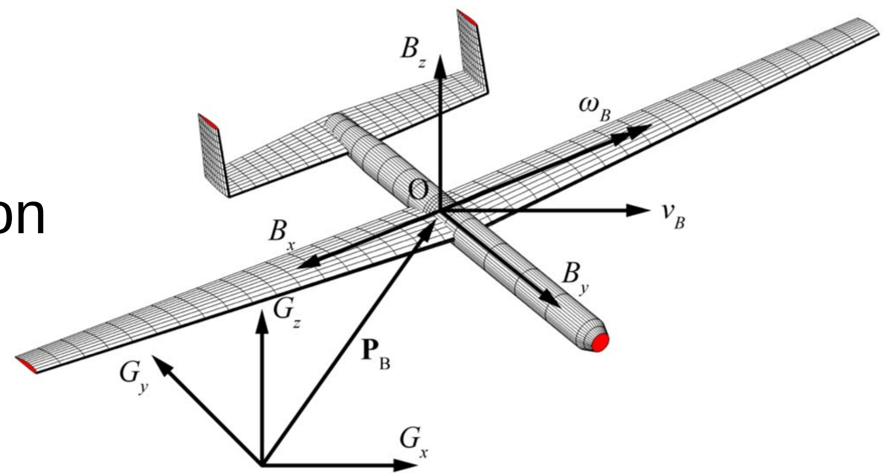
- Body reference frame propagation

$$\dot{\zeta}=-\frac{1}{2}\Omega_{\zeta}\zeta$$

Frame orientation
(4 quaternions)

$$\dot{P}_B=\begin{bmatrix}C^{GB} & 0\end{bmatrix}\beta$$

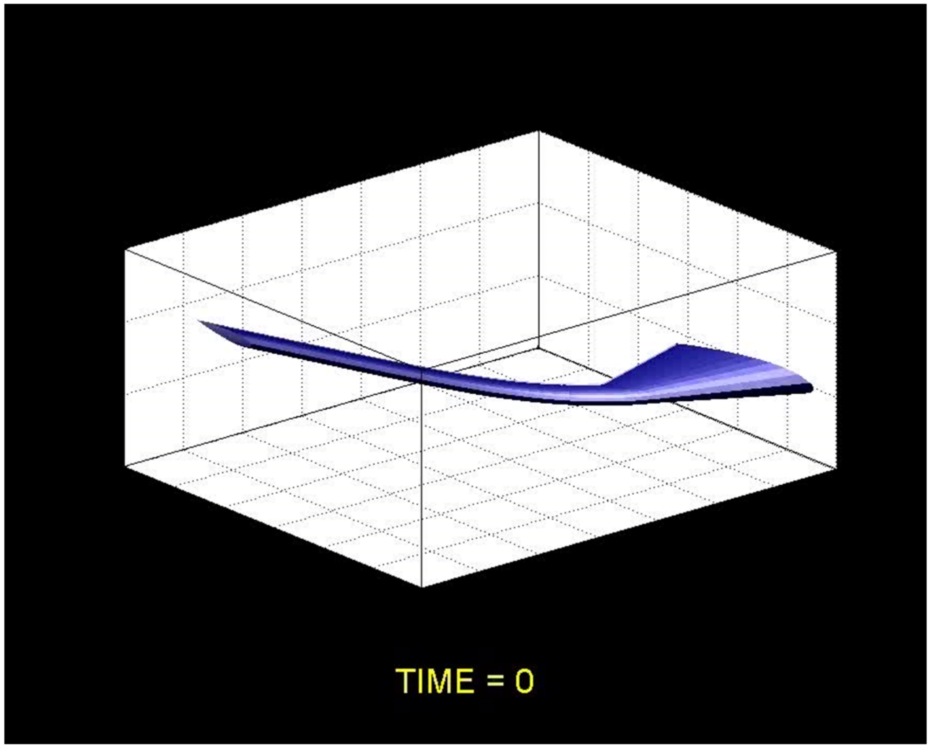
Inertial velocities (6 d.o.f.)

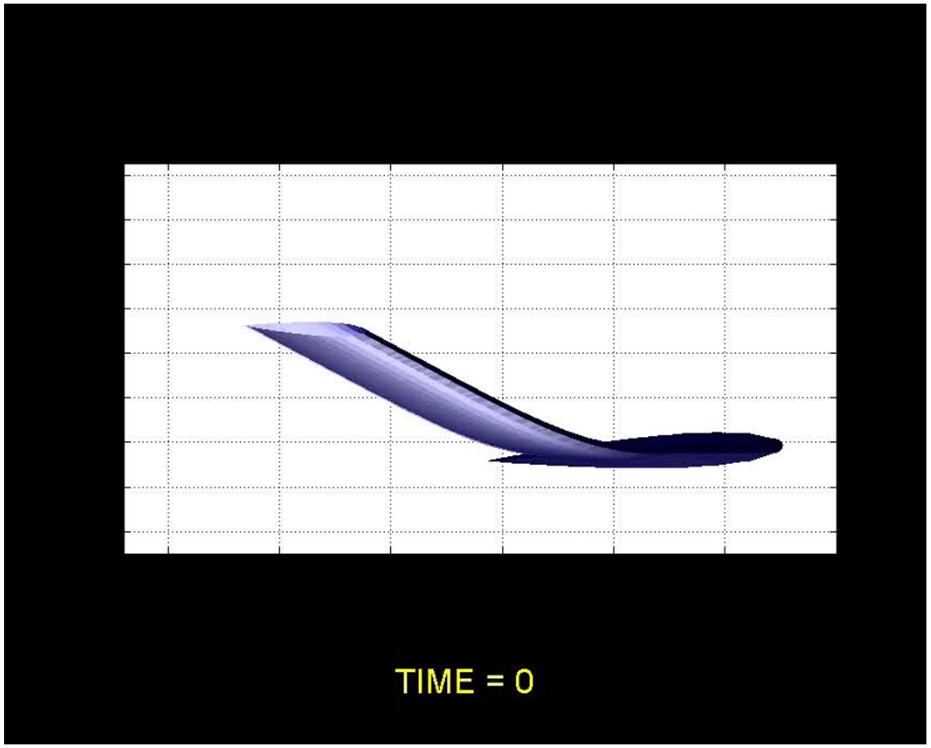


Numerical Studies

Flutter of Constrained Vehicle

- Similar to constrained wind-tunnel model (no body DOFs)
- Fixed root angle of attack (8 deg)
- Free stream velocity 1% higher than flutter speed

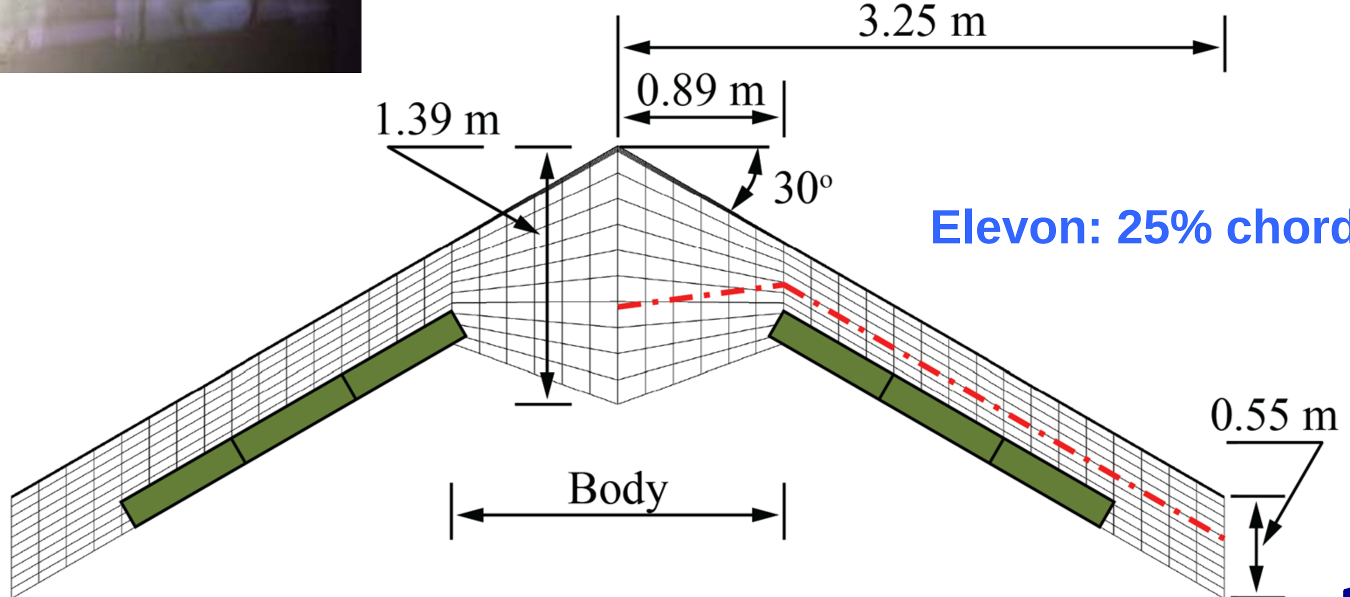




Coupled out-of-plane bending/torsion/in-plane bending mode

Blended-Wing-Body (BWB) Model

- Properties inspired from HiLDA (High Lift over Drag Active Wing) wind-tunnel model

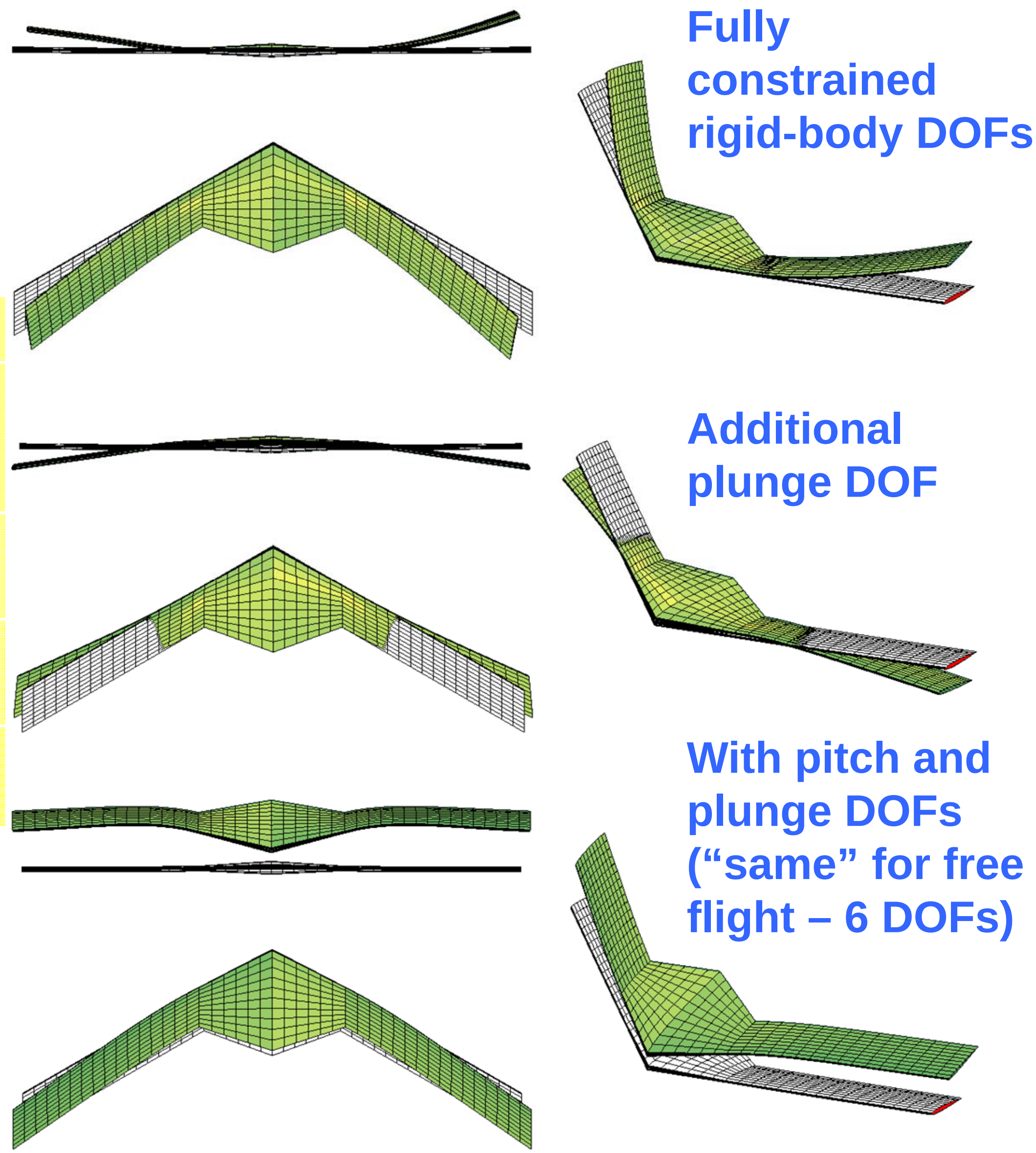


Comparison of Flutter Modes with Rigid-Body Constraints

All cases trimmed for 6,096 m (20,000 ft) altitude, same fuel condition

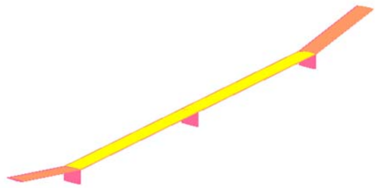
	Flutter Speed	Frequency
Fully constrained dof's	172.52 m/s	7.30 Hz
+ plunging	164.17 m/s	7.07 Hz
+ pitching and plunging	123.17 m/s	3.32 Hz
Free flight	123.20 m/s	3.32 Hz

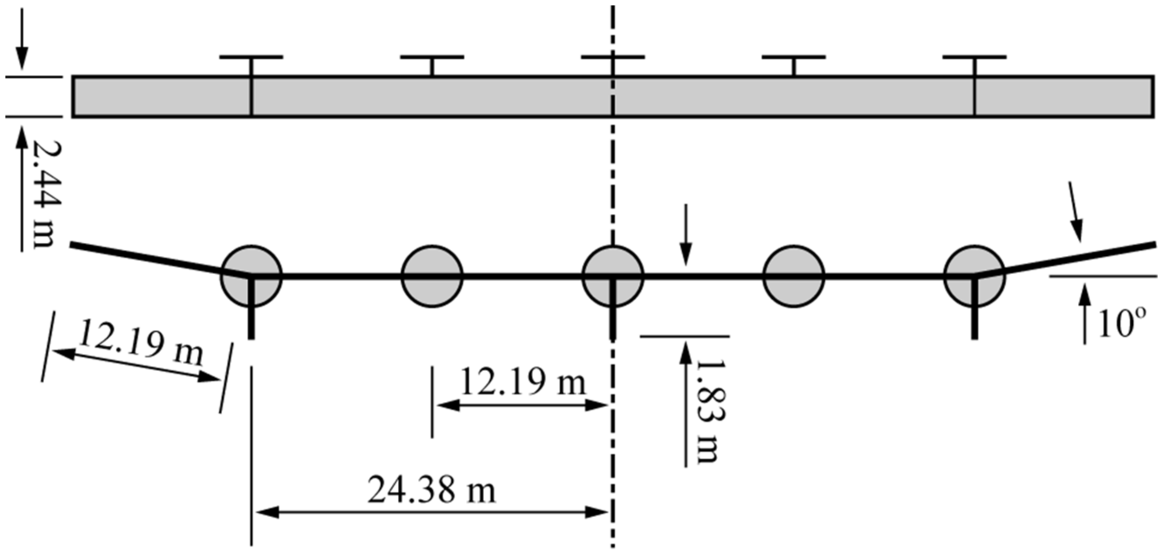
Traditional wind-tunnel setup maybe non-conservative – need rigid-body DOFs in the aeroelastic analyses, simulations, and tests



Highly Flexible Flying Wing Model

- Representative of Helios prototype[2]
  - Five engines and three pods
  - Payloads applied at center pod
  - Empty gross mass: 726 kg

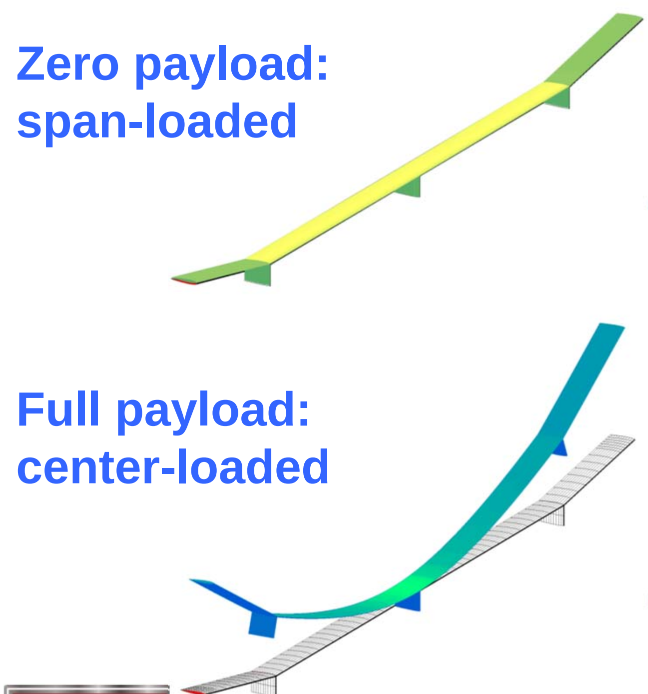


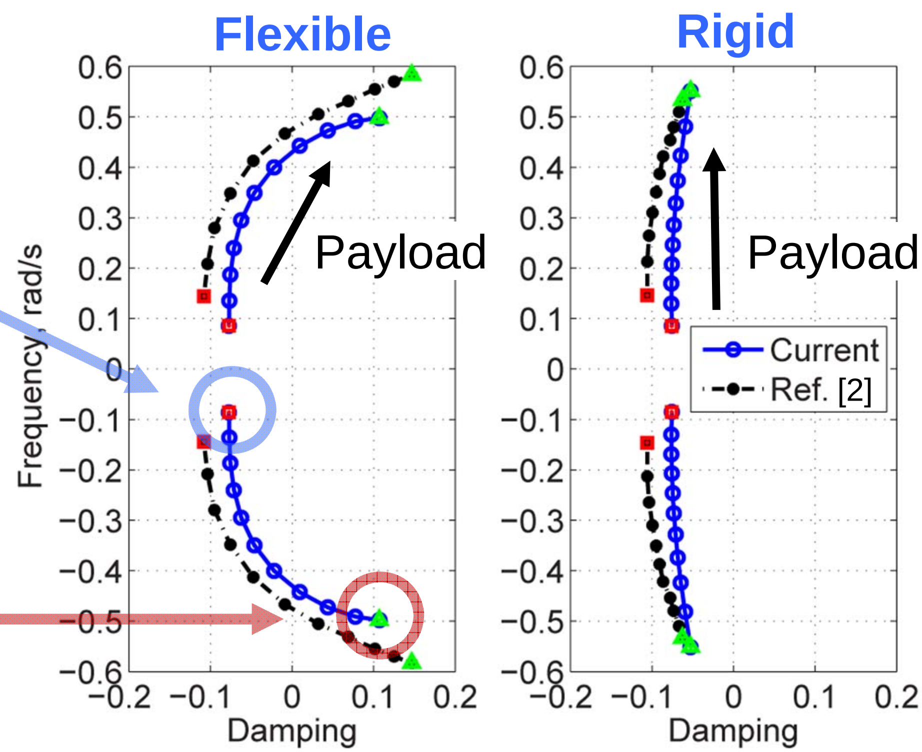


[2] Patil, M.J., and Hodges, D.H., "Flight Dynamics of Highly Flexible Flying Wings," *Journal of Aircraft*, Vol. 43, No. 6, 2006, pp. 1790-1798.

Trim Results and Flight Stability

- Speed: 12.2 m/s at sea level; Payload: 0 – 227 kg (at center pod)
- Linearization about each trimmed condition with increase of payloads
- Root locus for phugoid mode (left: flexible, right: rigid)
- Unstable phugoid mode for payload > 152 kg

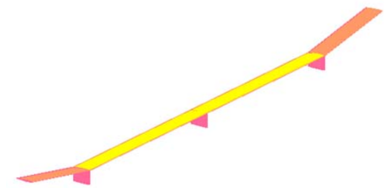


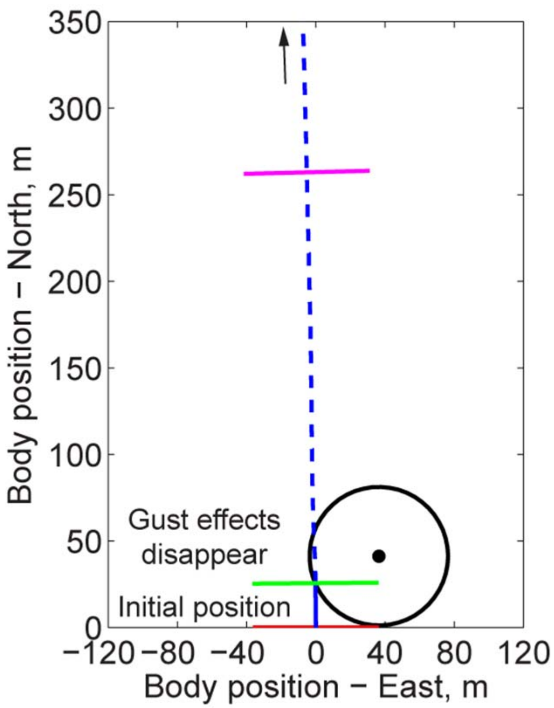


Nonlinear aeroelastic/flight dynamic characteristics dependent on trim conditions

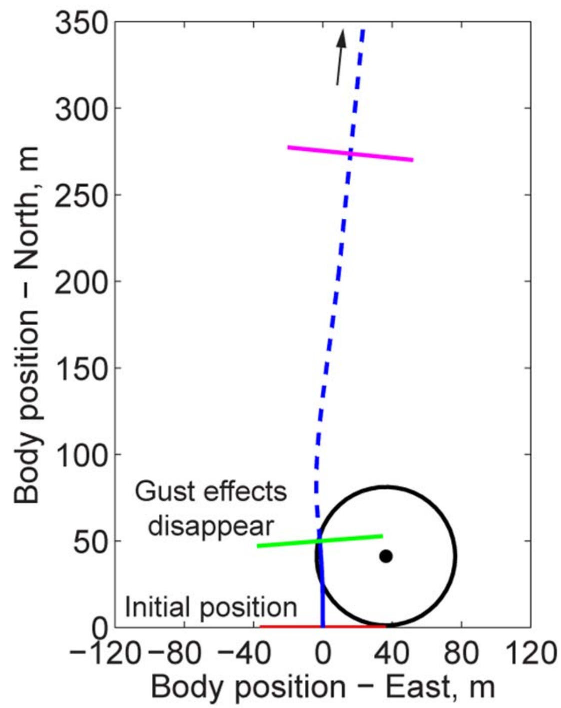
Non-symmetric Gust Input and Response – Fully-Loaded Configuration

- Payload: 227 kg; gust region radius: 40 m; maximum gust center amplitude: 10 m/s
- Non-symmetric discrete gust distribution:
  - gusts mainly applied on right wing

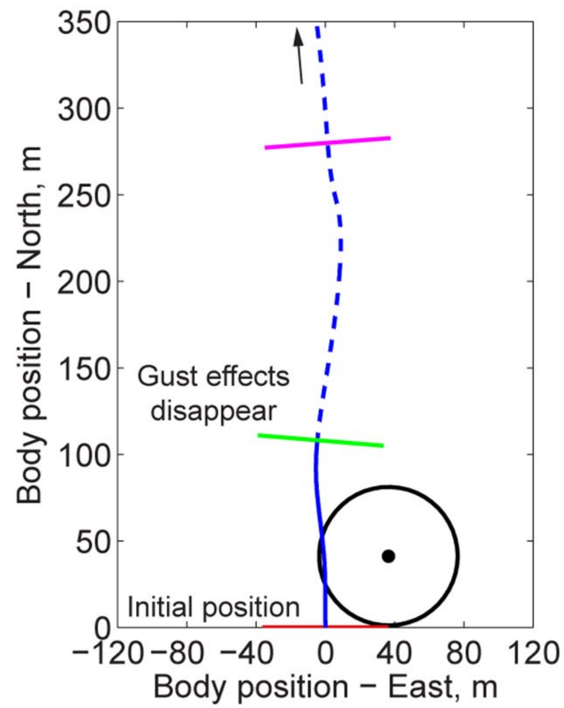




2 s gust duration



4 s gust duration

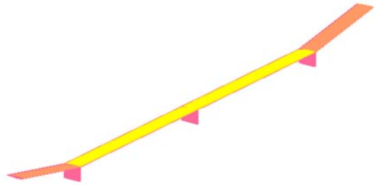


8 s gust duration

Gust duration impacts after-gust flight path

Instantaneous Vehicle Positions and Orientations

- Positions and orientations at 0, 5, 12, 18, 24, and 30 s, respectively



Flight Direction

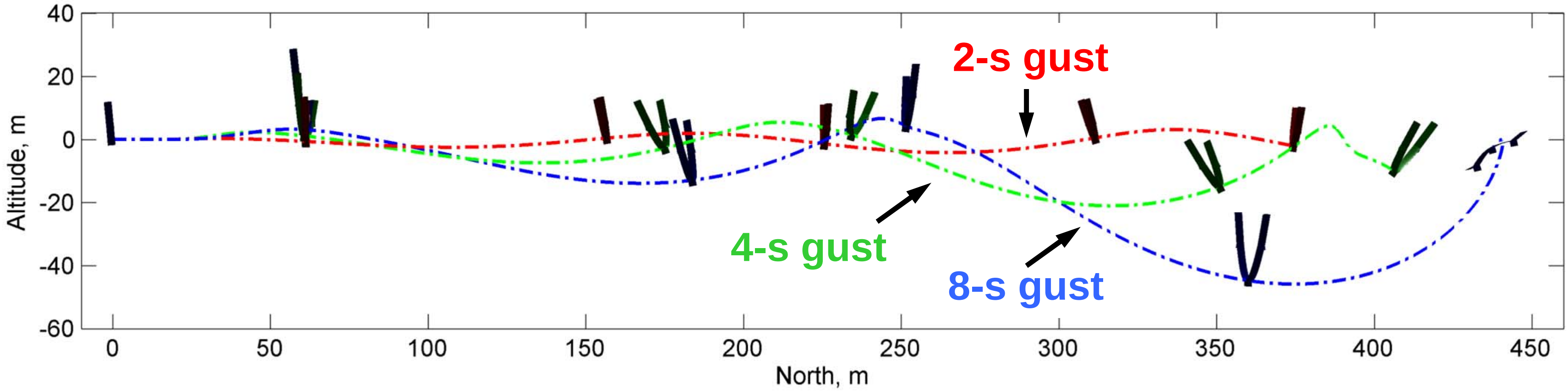
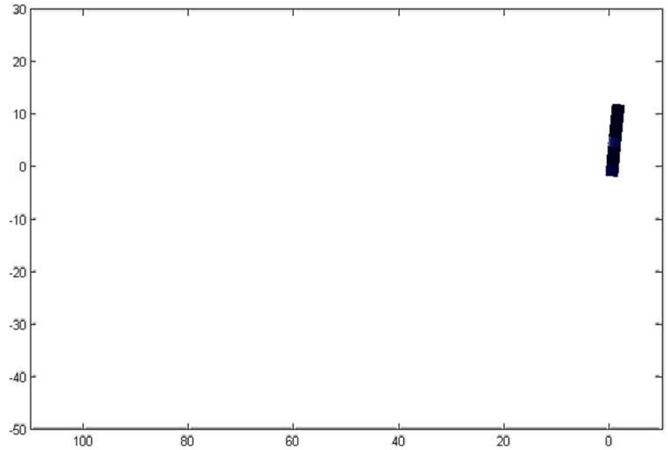
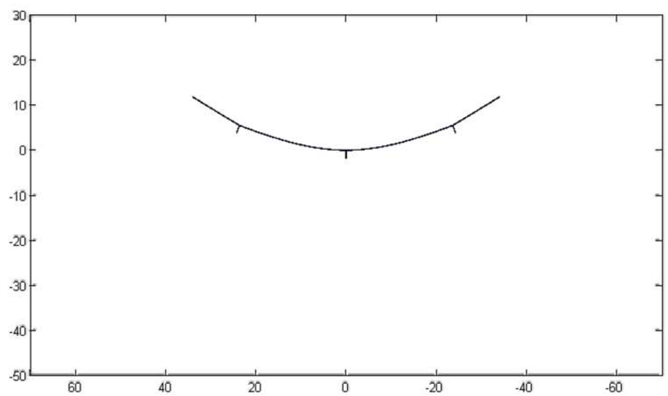


Illustration of unstable Phugoid mode

Animation of Vehicle Motion with Gust Perturbations

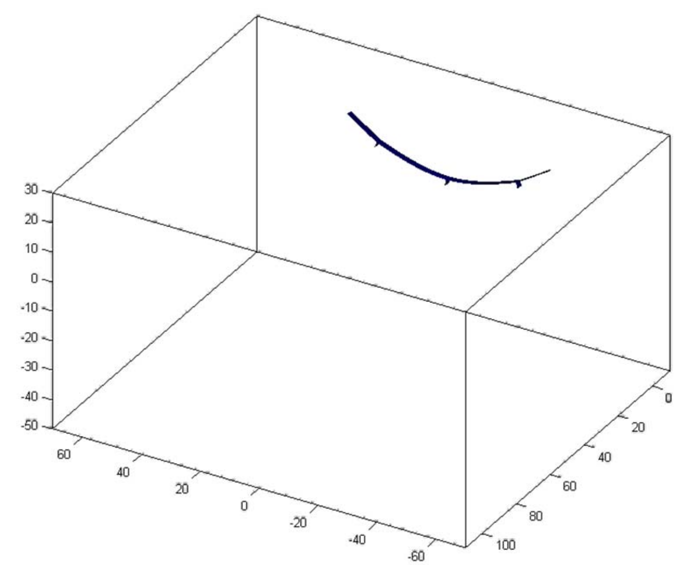


TIME = 0



TIME = 0

2-s gust
4-s gust
8-s gust



TIME = 0

Concluding Remarks

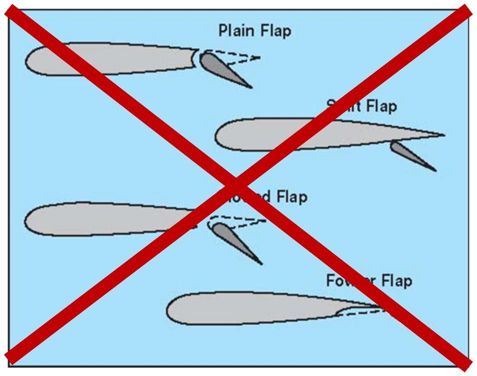
- Framework for modeling and analyzing highly flexible aircraft
  - Coupled nonlinear aeroelastic/flight dynamic simulation
  - Strain-based geometrically-nonlinear beam
  - Incompressible unsteady aerodynamics (with compressibility corrections and stall models)
  - Rigid-body flight dynamics
- Highly flexible aircraft have radically different behavior than conventional aircraft
  - Coupling between aircraft deformation and rigid-body motions changes flutter boundaries
  - Flutter boundary in free flight condition may be different from constrained flight
  - Finite amplitude gust can excite instabilities

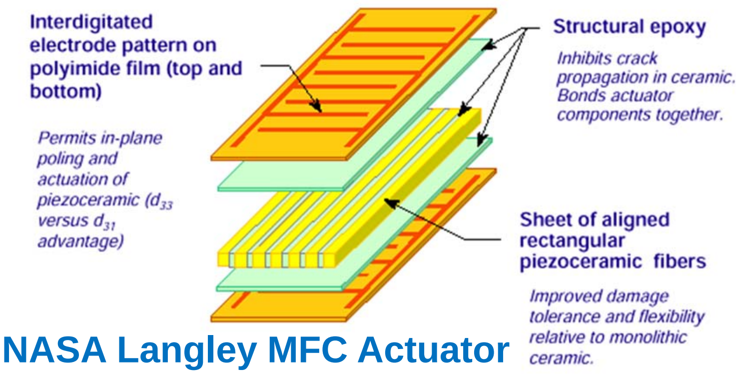
Concluding Remarks (Cont'd)

- What did we learn from the physics of highly flexible aircraft?
  - Operating (trim) condition should be the basis in weight, structural, and stability analyses
    - Deformed geometry other than the undeformed shape
  - Traditional linear solution to highly flexible aircraft aeroelasticity might not be sufficient
    - Nonlinear solution is required
  - Coupling between aeroelasticity and flight dynamics needs to be considered
    - Aeroelastic models should incorporate the rigid-body motion, and vice versa
    - Individual solutions might not be appropriate

Active Aeroelastic Tailoring and Control

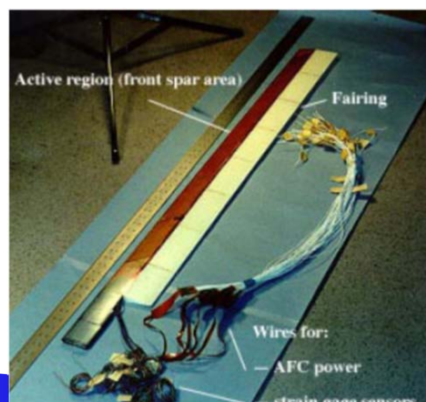
- Traditional approach for aerodynamic/flight control

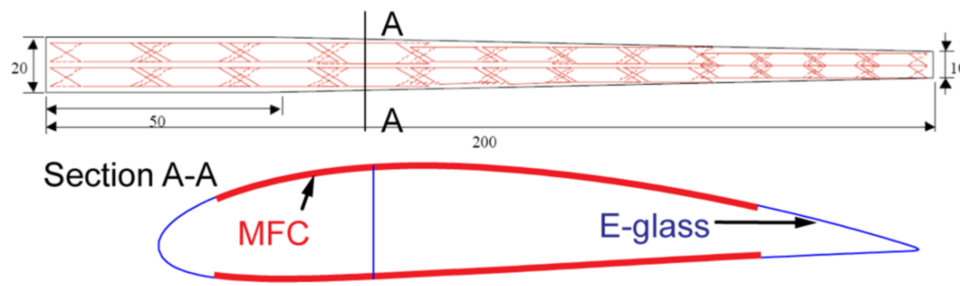




NASA Langley MFC Actuator

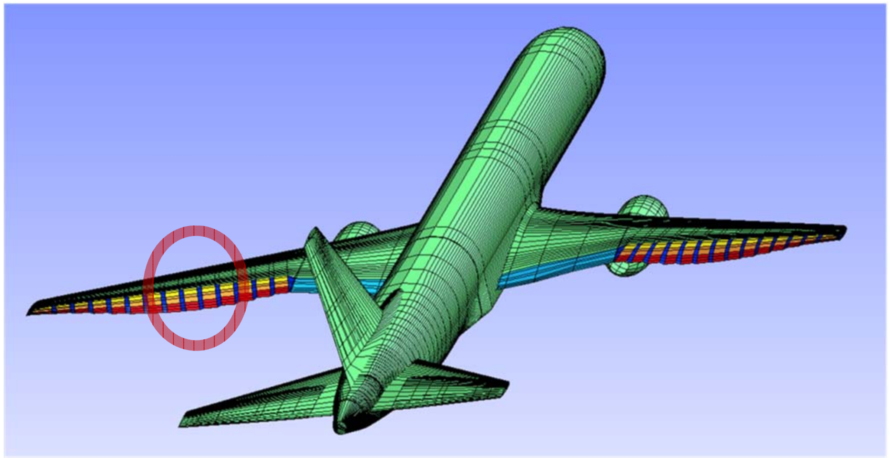
- Drag due to control surfaces
- Conformal wing shape changes
  - Integral strain actuation of bending/twist

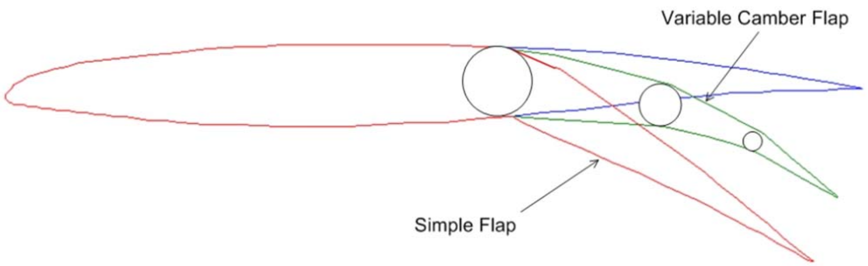




Wing Camber Change

- NASA VCCTEF



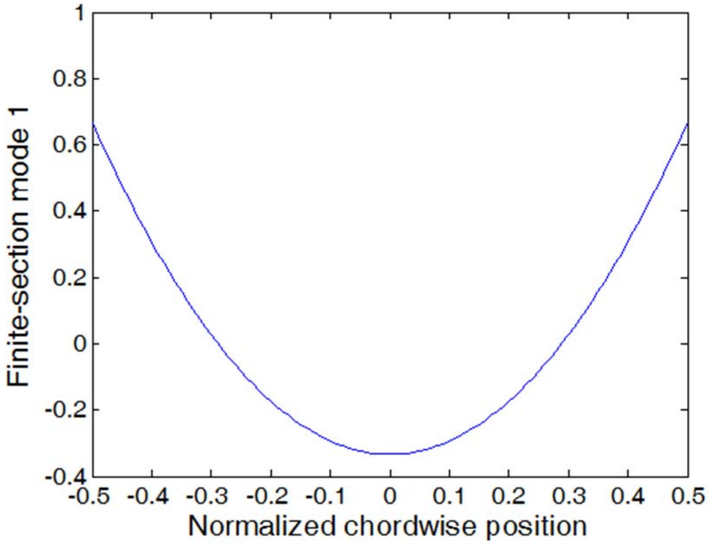


- Jointly proposed by UA/GA Tech/OSU/MSU
  - Full variable camber wing

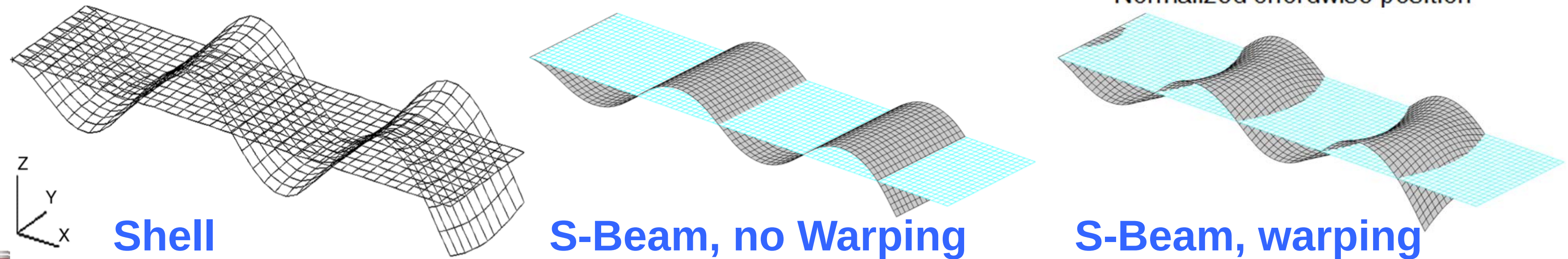
Recent Development

- Wing cross-sectional warping
  - Plate-like modeling capability with beam model
  - Augmented EoM with camber degrees (finite-section modes)

$$M(\varepsilon)\begin{Bmatrix}\ddot{\varepsilon}\\(\ddot{q}_n)\\\dot{\beta}\end{Bmatrix}+C(\varepsilon,\dot{\varepsilon},\beta)\begin{Bmatrix}\dot{\varepsilon}\\(\dot{q}_n)\\\beta\end{Bmatrix}+K\begin{Bmatrix}\varepsilon\\(q_n)\\b\end{Bmatrix}=\begin{Bmatrix}R_\varepsilon\\R_{q_n}\\R_b\end{Bmatrix}$$



- Impact on aeroelasticity, flight dynamics, and control -> on-going



Camber shape control for higher flight efficiency

Linear Strain Modes

- Approximate solutions using strain modes

$$\varepsilon(s,t) = \Phi(s)\eta(t)$$

- Modes from elastic EOM

$$\begin{bmatrix} M_{FF} & M_{FB} \\ M_{BF} & M_{BB} \end{bmatrix} \begin{Bmatrix} \ddot{\varepsilon} \\ \dot{\beta} \end{Bmatrix} + \begin{bmatrix} K_{FF} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \varepsilon \\ b \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

$$\Downarrow$$

$$\Phi_C = \begin{Bmatrix} \Phi_F \\ \Phi_B \end{Bmatrix}$$

- Only take the elastic components of the modes

$$\Phi(s) = \Phi_F$$

Modal Equations

$$M_{FF}\ddot{\varepsilon} + M_{FB}\dot{\beta} + C_{FF}\dot{\varepsilon} + C_{FB}\beta + K_{FF}\varepsilon = R_F$$

$$M_{BF}\ddot{\varepsilon} + M_{BB}\dot{\beta} + C_{BF}\dot{\varepsilon} + C_{BB}\beta = R_B$$

$$\dot{\lambda} = F_1\begin{Bmatrix}\ddot{\varepsilon}\\ \dot{\beta}\end{Bmatrix} + F_2\begin{Bmatrix}\dot{\varepsilon}\\ \beta\end{Bmatrix} + F_3\lambda$$

$$\Downarrow$$

$$\bar{M}_{FF}\ddot{\eta} + \bar{M}_{FB}\dot{\beta} + \bar{C}_{FF}\dot{\eta} + \bar{C}_{FB}\beta + \bar{K}_{FF}\eta = \bar{R}_F(\eta,\dot{\eta},\ddot{\eta},\beta,\dot{\beta})$$

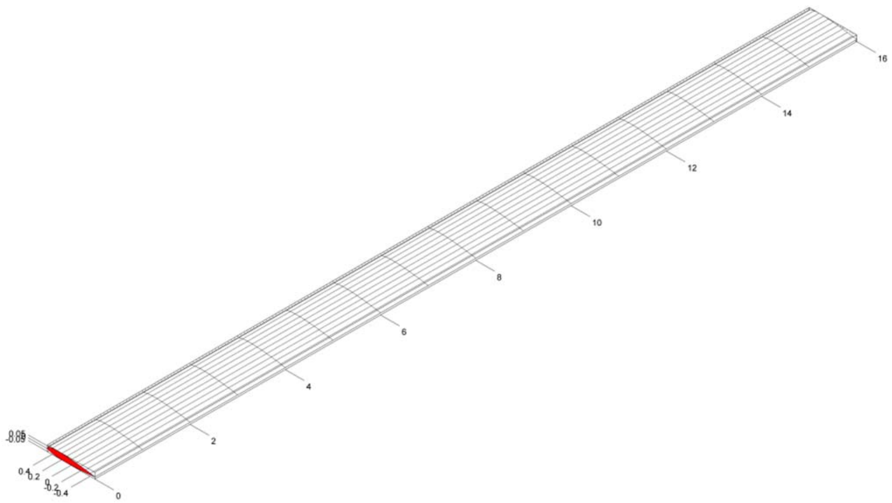
$$\bar{M}_{BF}\ddot{\eta} + \bar{M}_{BB}\dot{\beta} + \bar{C}_{BF}\dot{\eta} + \bar{C}_{BB}\beta = \bar{R}_B(\eta,\dot{\eta},\ddot{\eta},\beta,\dot{\beta})$$

$$\dot{\lambda} = \begin{bmatrix}\bar{F}_{1F} & F_{1B}\end{bmatrix}\begin{Bmatrix}\ddot{\eta}\\ \dot{\beta}\end{Bmatrix} + \begin{bmatrix}\bar{F}_{2F} & F_{2B}\end{bmatrix}\begin{Bmatrix}\dot{\eta}\\ \beta\end{Bmatrix} + F_3\lambda$$

Highly Flexible Wing

- Beam properties:

Length (m)	16
Chord (m)	1
Mass per length (kg/m)	0.75
x-sectional *c.g.* position	50% chord
x-sectional shear center	50% chord
Rotational inertia (kg·m)	0.1
Flat bending rigidity (N·m^2)	2.00×10^4
Edge bending rigidity (N·m^2)	4.00×10^4
Torsional rigidity (N·m^2)	1.00×10^4



- Nonlinear flutter speed: 23 m/s

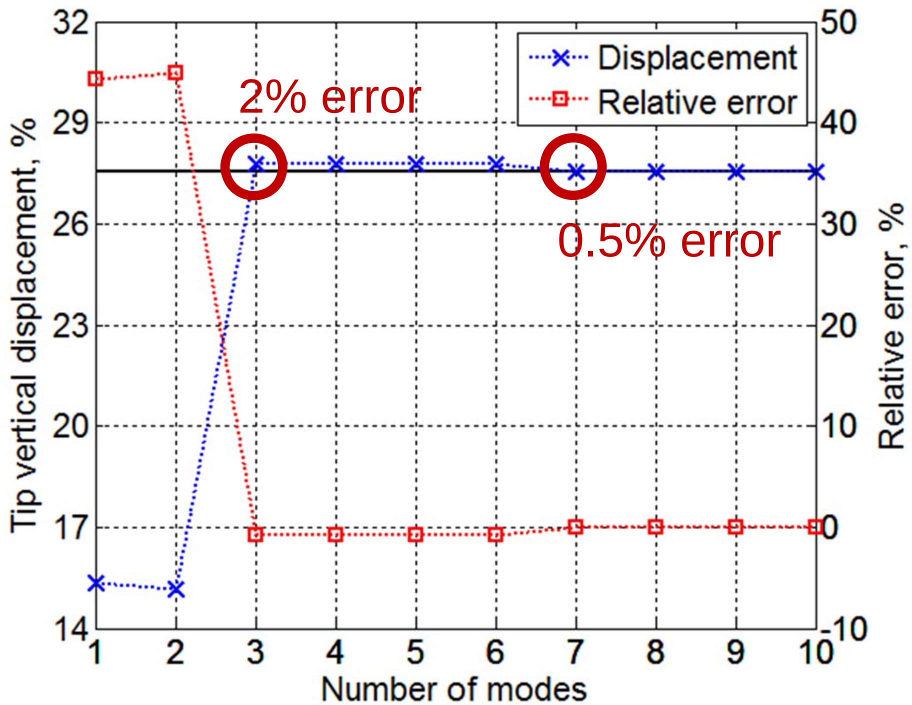
	Ref. 3*	Current (linear)	Current (nonlinear)
Velocity (m/s)	32.2	32.2	23.3
Frequency (Hz)	3.60	3.60	1.61

[3] Patil, M.J., Hodges, D.H. and Cesnik, C.E.S., "Nonlinear Aeroelasticity and Flight Dynamics of High-Altitude Long-Endurance Aircraft," *Journal of Aircraft*, Vol. 38, No. 1, 2001, pp. 88-94.

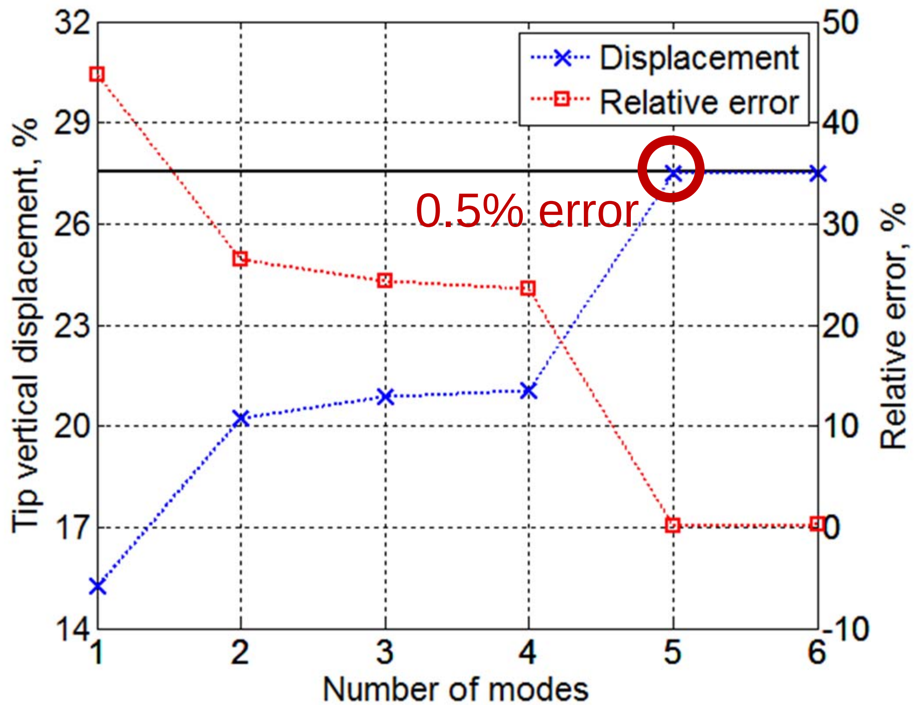
Modal-Based Static Solution

- Convergence of static solutions with different number of modes

Modes about undeformed shape



Modes about deformed shape

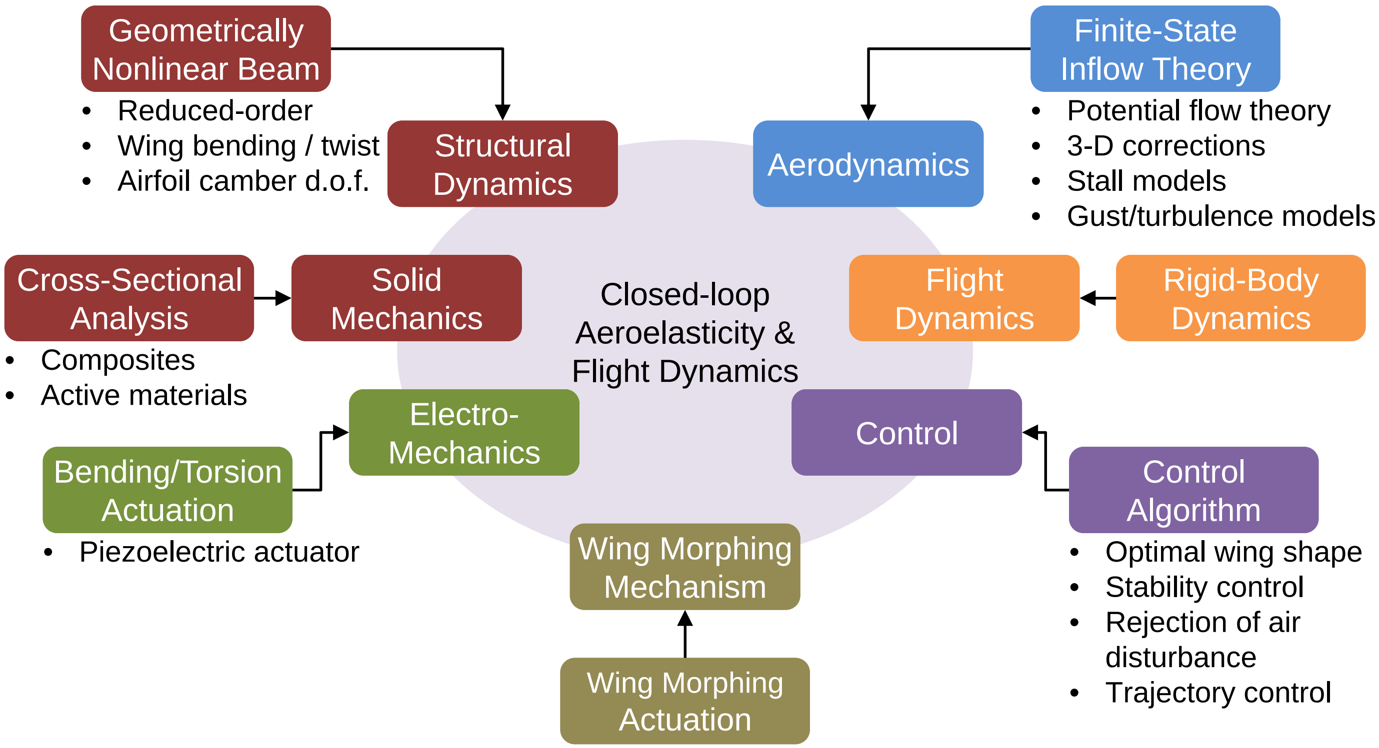


- For more discussion:

[4] Su, W., and Cesnik, C.E.S., "Strain-Based Analysis for Geometrically Nonlinear Beams: a Modal Approach," *Journal of Aircraft*, Vol. 51, No. 3, 2014, pp. 890–903. (doi: 10.2514/1.C032477)

Fewer modes required if modes are obtained about deformed shape

Multi-disciplinary Simulation of Flight Vehicles



An active aero-servo-elastic simulation system